Prospects for Fuel Derived from Biomass as a Major Transportation Sector Energy Carrier

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"Major transportation energy carrier"

Share of transportation energy supply greater than accessible via low-level fuel blends

Use of biofuels as *primary* transportation sector energy carriers (energy source for $\geq$ 50% of mobility) of particular interest for evaluating potential to address key challenges

- **Sustainability (especially carbon cycle)**
- **Security**
- **Limited fossil fuel production capacity**

Analysis will be based on cellulosic ethanol

The potential of biofuels is not limited to cellulosic ethanol

Many of the factors determining the potential of biofuels are not fuel-specific

To be Major Transportation Energy Carriers, Biofuels Must Have

Generation of net energy

Acceptable & preferably low cost

Acceptable & preferably beneficial environmental consequences

Adequate resource base, with acceptable & preferably small impacts on land uses other than commercial production of plants

Net Energy & Efficiency (Cellulosic Ethanol)

	State of Technology		
	Near-Term	**Mature**	**Comments**
Feedstock Production (Fuel & power input/Biomass high heating value)[1]			
	~	< 0.04	Widespread consensus very small.
Energy Out:in (Fuel & power output)/(Fuel & power input)[2]			
	4.4	≥6.6	No informed argument not >> 1
Displaced fossil fuel (FFE_{out})/(FFE_{in})[3]			
	5.7	≥9	No informed argument not >> 1
Process (Fuel & power output/Biomass high heating value)			
	0.50[2]	0.73[4]	Compares favorably with many competing processes, especially on a displaced fossil fuel basis
Photosynthetic (Biomass HHV/Incident sunlight)[4]			
	≤ 0.02	≤0.04	Impacts land requirements

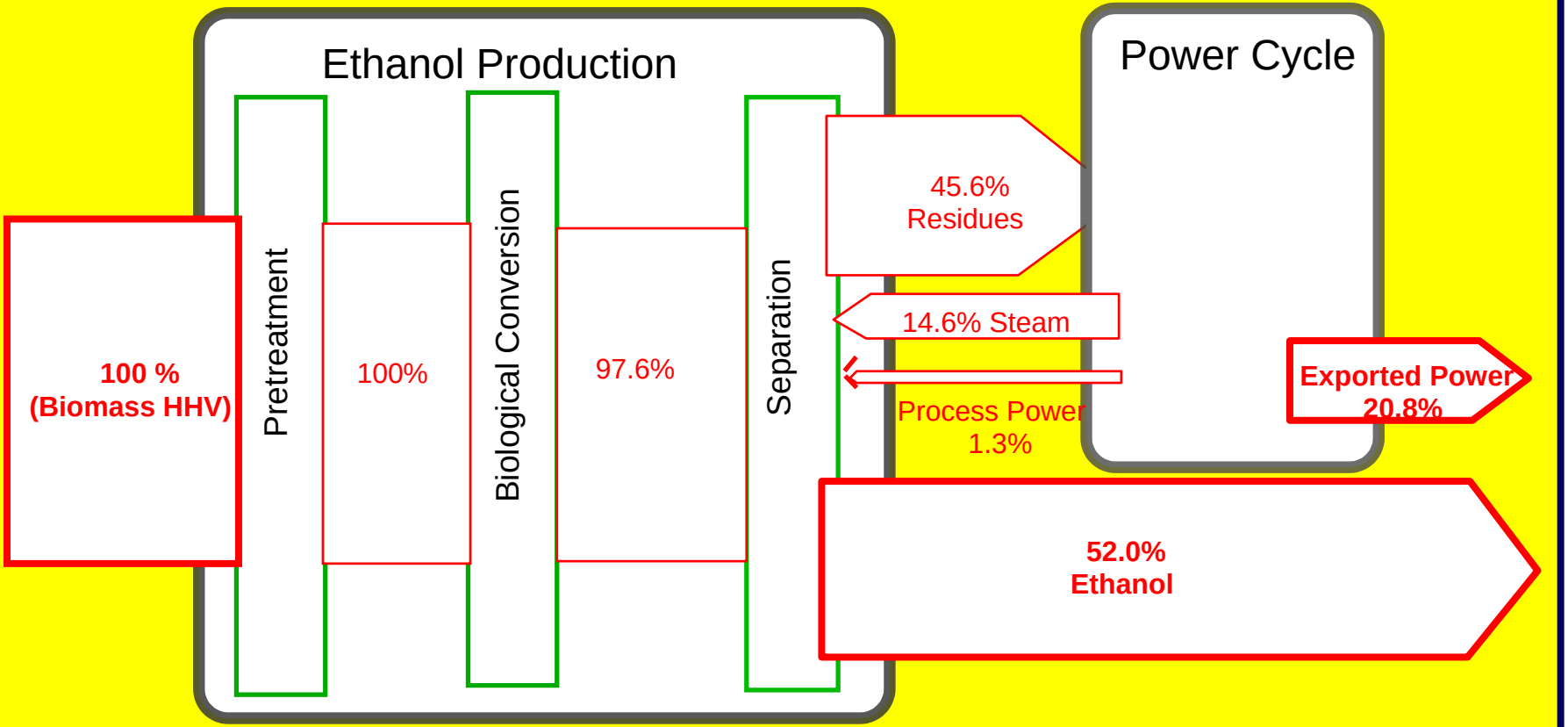
[1] GREET model

[2] Includes feedstock production and processing; Lynd, 1996 (update in-progress).

[3] As for [2]; small power input not converted to FFE basis.

[4] Current estimate, analysis underway as part of the RBAEF project.

Co-Production of Ethanol & Power via Mature Technology



Width of arrows proportional to energy flows

Power cycle based on gasification, fuel cells, wit

	Production Efficiency	
	Dedicated	Co-Produced
Ethanol	0.52	0.77
Power	0.47	0.65
Overall		0.73

 Co-production of ethanol, HDV fuels also very interesting, under examination

Cost

	Near-Term	Mature	Comments
Feedstock	$35-$50/ton	Less	Not a major constraint. Cellulosic biomass @ $40/ton = $2.3/GJ = oil @ $13/barrel.
Cost of cellulosic ethanol (nth plant)[1]	≥ $1.20/gal	~ 50¢/gal	Cost of processing main obstacle.

[1] From farmed biomass @ $42/tonne, Lynd et al., 1996

Key factor underlying the high cost of current processes

The recalcitrance of cellulosic biomass (the cost of fermentation, product recovery, residue processing, receiving & handling, feedstock do not prevent very low-cost processes)

Lowest cost mature technology scenarios for overcoming the recalcitrance of cellulosic biomass involve biological processing

Progress will depend on

Advanced pretreatment

Advanced technologies for biologically-mediated hydrolysis

A stream-lined process achieving high yield would have *very* low cost as determined by any reasonable costing framework

Pretreatment
- Low energy
- High yield
- No detox.

→

Fermentation
- Cellulose & hemicellulose
- No dedicated cellulase production
- High yield
- Sufficient [EtOH]

→

Product Recovery & Downstream Processing

- AFEX appears to meet most requirements.
- Engineering & optimization remain to be completed but should be doable.
- Fermentation of hemicellulose oligomers advantageous.

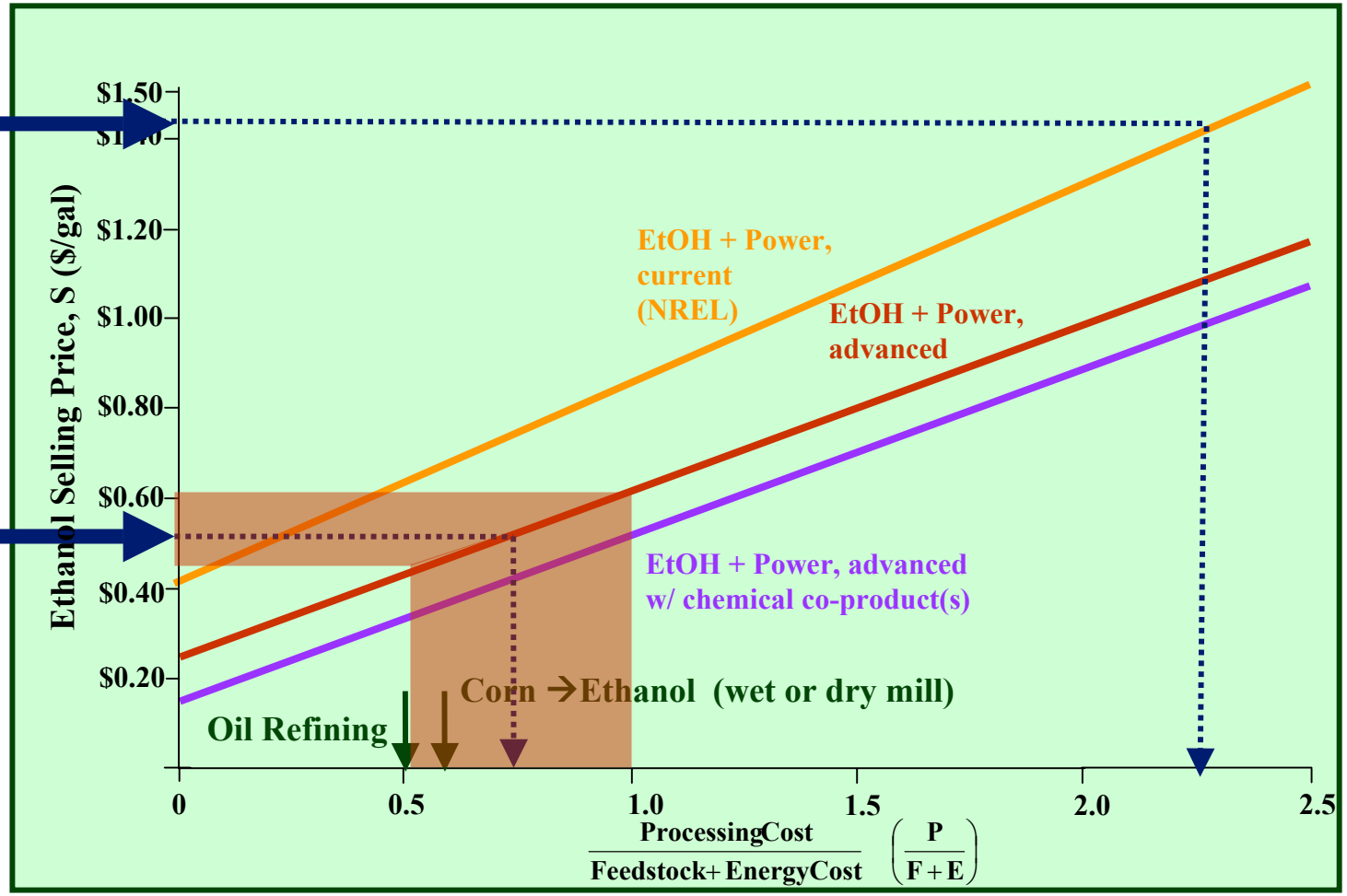
- Modeling, recent lab results supports kinetic & bioenergetic feasibility.
- Requires a major biotechnology development effort.
- Magnitude of challenge/effort not larger than regularly encountered in the pharmaceutical industry.
- Process development with a microbial rather than enzymatic paradigm.

- Modest improvements possible, desirable, but not necessary

The Selling Price of Ethanol Production via Mature Technology

NREL Base Case
Wooley et al., 1999
$1.44/gal

Detailed design study, most likely case
Lynd et al., 1996
50 ¢/gal



Ethanol selling price exhibits a linear dependence on P/(F+E):

Without co-products:

$$S = \frac{1}{Y_{P/F}} P + \frac{(F+E)}{Y_{P/F}}$$

With co-products:

$$S = \left(\frac{1}{Y_{P/F}\left(1 - \sum_i f_i\right)} \right) P + \frac{(F+E) - \sum_i S_i \cdot f_i \cdot Y_{i/F}}{Y_{P/F}\left(1 - \sum_i f_i\right)}$$

$Y_{P/F}$ = gal ethanol/ton feedstock

f_i = fraction feedstock → i^{th} co-product

$Y_{P/F}$ = gallons ethanol/ton feedstock

S_i = $/unit co-product

$Y_{i/F}$ = units co-product/ton feedstock

Resource Issues are Important

Useful framework

$$\text{Benefits } (+\text{or}-) = \left(\frac{\text{Benefits}}{\text{Unit Utilized}}\right) \times \left(\text{Units Utilized}\right)$$

Life Cycle Issues

Perennial grass compared to row crops

- **100-fold less erosion**
- **7 to 10-fold less herbicides, pesticides**
- **Much higher nutrient capture efficiency**
- **Increased organic matter, soil fertility**

Near zero net greenhouse gas emissions for many bioenergy scenarios

In general, production & utilization of cellulosic biomass score very well

Resource Issues

Even with positive effects per acre, an acre devoted to bioenergy production is not available exclusively for

Food production

Wildlife habitat/biodiversity

Recreation

A more challenging set of issues for bioenergy to address

The Biomass Resource Base

Radically different conclusions have been reached

- Biomass becomes the largest energy source supporting humankind in the (Renewables-Intensive Global Energy Scenario, Johanssen et al., 1993).
- Biomass share of world energy supply will equal that of oil in 2050 and be as large as any other resource (Kassler, Shell Petroluem Ltd, 1994).
- Biomass will eventually provide over 90% of U.S. chemical and over 50% of U.S. fuel production (Biobased Industrial Products, NRC, 1999).
- To provide ethanol to replace all gasoline used in the [U.S] light-duty fleet, we estimate it would be necessary to process the biomass growing on 300 to 500 million acres. (Lave et al., 2002).
- Large scale biofuel production is not an alternative to the current use of oil and is not even an advisable option to cover a significant fraction of it (Giampetro et al., '97).

Key variables impacting availability of biomass for non-food uses

Biomass productivity (tons/acre*yr)

Vehicle efficiency (miles/gallon)

Food production efficiency (calories, protein/acre)

Biomass Productivity: Some Observations

Assumed values vary widely in different analyses (e.g. 0.5 to 15 tons/acre*year)

Some current benchmarks (tons/acre*year)

Corn kernels:	3.5 tons/acre*year (U.S. average)
Corn, above-ground plant matter:	7 tons/acre*year (U.S. average)
Perennial grass (typical quoted value):	~ 6 tons/acre*year

If increasing the BTU productivity of perennial grasses (a relatively NEW objective) received an effort comparable to that put into increasing the grain productivity of corn, what would be reasonable to expect?

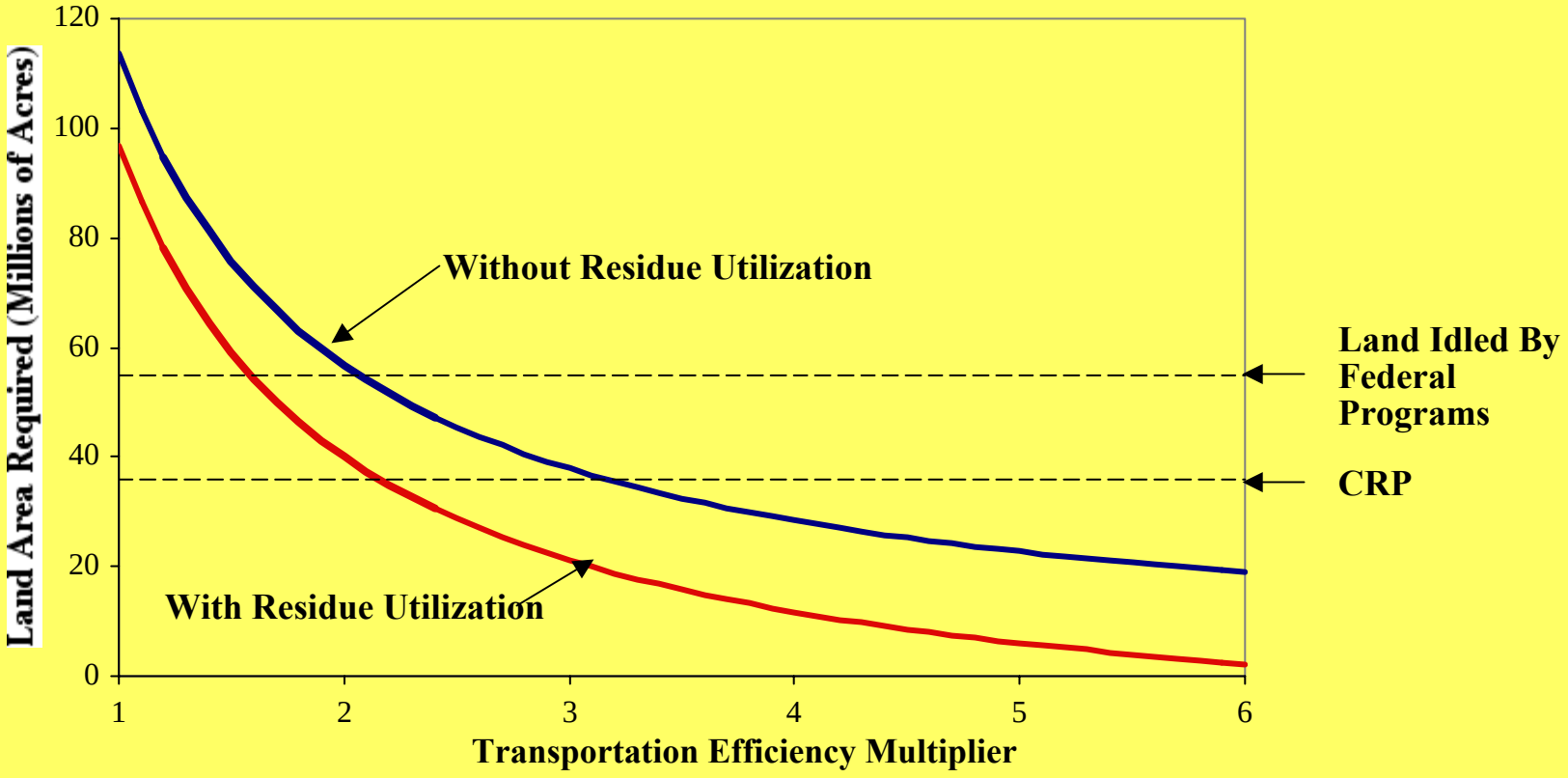
Perennial grass productivity should be higher than corn due to

- More solar energy striking the leaves over the growing season
- Longer growing season
- Much less energy diverted to seeds (non-photosynthetic)

- **The subject of intensive analysis as part of the RBAEF project.**
- **Current projection: 2x average grass productivity --> 12 tons/acre*year in 20 to 30 years.**

Most scenarios assume energy crops will be grown on a large amount of relatively low productivity land. Habitat disruption is minimized by using a smaller amount of high productivity land.

Land Area Required for Current U.S. Light Duty Mobility in Relation to Vehicle Efficiency



- LDV VMT = 2.1 trillion vehicle miles traveled
- Waste availability: 200 million dry tons
- Switchgrass productivity: 12 dry tons/acre/year (mature technology)
- Ethanol yield: 100 gallons/dry ton

Land area requirements should be multiplied by about 1.6 for total transportation sector energy requirements including heavy duty vehicles, planes, and trains.

High Vehicle Efficiency

Possible ***(2020 estimates from Friedman, 2003)***

Today: '04 Prius (mid-size), 56 mpg

By 2020, fuel savings > added vehicle cost (hybrids + advanced technology)[1]

Fleet average: 50 to 60 mpg.

A feet made up only of pickups, minivans, and SUVs could still reach 50 mpg.

Desirable

Direct: Reduces GHG emissions, oil imports & depletion rate.

Indirect: Increases the feasibility of alternatives to petroleum

Difficult to imagine a sustainable transportation sector without it

Scenario	High efficiency vehicles compensate for…
Renewable power/H_2	Otherwise low travel radius
Renewable power/batteries	Otherwise low travel radius
Biomass/ethanol	Otherwise large land requirement

Implicit in transportation scenarios featuring energy storage as H_2

Food Production Efficiency: Some Observations

Strongly impacted by dietary trends - the amount and kind of meat consumed in particular.

Tremendous potential elasticity

Land to feed U.S. population in the most land-efficient way possible: ~ 20×10^6 acres[a]

Land currently used: > 400 million acres

[a] Bruce Dale

Although food production is usually assumed to remain static in analyses of the role of biomass as an energy source,demand for cellulosic feedstocks due to cost-competitive processing technology would very likely result in large changes in food production.

Coproduction of processing feedstock and animal feed is one likely change.

Integrated Production of Processing Feedstocks and Feed Protein*

Concept

Composition & productivity comparison

Crop	Mass Productivity (tons/acre/year)	Protein (Mass Fraction)	Protein Productivity (tons/acre/year)
Switchgrass	4.0 – 12	.08 -0.12 (early cut)	0.32 – 1.4
Soybeans	1.1 – 1.3	0.36 (bean only)	0.40 – 0.45

- **Consumption of calories and protein by livestock 10x that by humans in the U.S.**
- **Currently the U.S. devotes ~ 70 million acres to production of soybeans, used primarily as a protein supplement for animal feed**
- **Production of perennial grass could potentially produce the same amount of feed protein per acre while producing a large amount of feedstock for energy production**
- **Requires readily foreseeable processing technology to recover feed protein**

*Concepts proposed by Bruce Dale & under investigation as part of the RBAEF project.

The Availability of Biomass for Non-Food Uses is a Much More Elastic Quantity Than Usually Assumed

***Would like to know*:** $\dfrac{\text{Land Required to Meet a Specified Need (e.g. Transportation)}}{\text{Land Available}}$

Driving habits, demography

$\dfrac{1}{\text{Vehicle Efficiency}}$

$\dfrac{1}{\text{Conversion Efficiency}}$

Allowance for residues

$\dfrac{1}{\text{Ag. Productivity}}$

$$= \frac{\text{Population x mi/person x energy/mile x ton biomass/energy x } (1 - f_{residues}) \text{ x acres/ton}}{\text{Available land - Population x } 1/\eta_{distribution} \text{ x nutrition/person x acres/nutrition}}$$

Sustainable land base, w/ allowance for nature

Distributional losses

Calories, protein per person

$\dfrac{1}{\text{Ag. Productivity}}$

***Considering the range of values these largely independent parameters might be assumed to take in a future scenario (e.g. 50 years hence)*:**

$$= \frac{\text{1.5-fold x 3-fold x 4-fold x 2-fold x 2-fold x 5-fold}}{\text{3-fold - 2-fold x 1.5-fold x 1.5-fold} \geq \text{5-fold}} = \frac{\text{320-fold}}{\text{3-fold - 20-fold}}$$

Some Illustrative Scenarios

(the math is not hard)

Calibration points

Total U.S. cropland: ~400 million acres

Land planted in soybeans: ~70 million acres

Idled in conservation reserve program: ~30 million acres

Land required to satisfy current U.S. LDV mobility (~2/3 of total transport energy)

Scenario	Biomass Productivity (tons/acre*yr)	Fleet mpg	Integrated Feed/Feedstock Coproduction	Additional Land* (Million Acres)
a. Status quo	4	20	No	394**
b. High productivity	12	20	No	131
c. (b + high mileage)	12	50	No	52
d. "Motivated"	12	50	Yes	0

* Land in addition to that currently devoted to agriculture.

**$(2.1 \times 10^{12}$ mi/yr)*(1 gal gas/20 mi)*(1.5 gal EtOH/gal gas)*(1 ton biomass/100 gal EtOH)*(1 acre*yr/4 ton) $= 394 \times 10^{6}$ acres

Approaches to Energy Planning & Analysis

1. Bury our heads in the sand. **Pretend that energy challenges are not real or will go away.**

2. Extrapolate current trends. **Often championed by "realists".**

3. Hope for a miracle. **Acknowledge the importance of sustainable and secure energy supplies, but dismiss foreseeable options as inadequate to provide for the world's energy needs & calls for "disruptive" advances in entirely new technologies.**

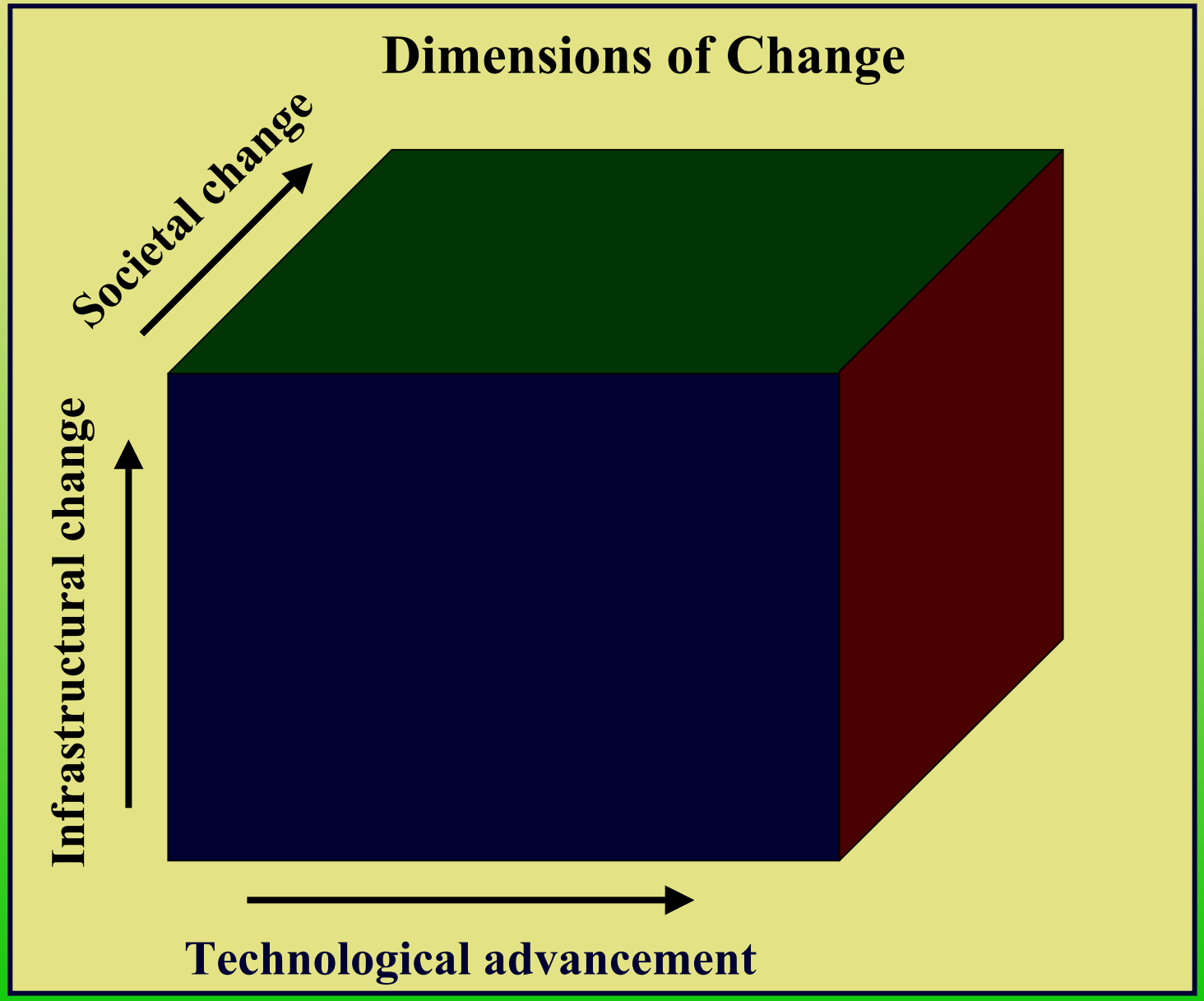
4. Innovate & change. **Define sustainable futures based on mature but foreseeable technologies in combination with an assumed willingness of society to change in ways that increase resource utilization efficiency. Then work back from such futures to articulate transition paths that begin where we are now.**

#1 and #2 do not offer solutions to sustainability and security challenges.

#3 should be pursued but is too risky to be a basis for planning.

#4 is the most sensible choice if it is assumed that problems associated with sustainability and security are important to solve.

If we are to achieve a sustainable and secure energy future, the question is not if we will change but what we will change.



Cellulosic Ethanol - Conventional Wisdom

- **Generally not regarded as viable primary energy storage medium for a sustainable transportation sector**

- **But transition issues are generally thought to be small**

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Almost always analyzed in a short-term context with status-quo assumptions

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Cellulosic Ethanol - "High Beam" Perspective

- **Price, fuel utility, GHG and criteria emissions, & soil fertility all have potential to be strongly favorable**

- **Land requirements are potentially modest**

QuickTime™ and a
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<u>But</u>

- **But realizing potential requires innovation and change…**

  as do H_2 mobility chains and most if not all other paths to a world supported by sustainable and secure energy sources

Working Hypotheses Supported by In-Progress Analysis

Cellulosic ethanol, & perhaps other biomass fuels, merit consideration as primary transportation energy carriers for the indefinite future.

Hydrogen-based mobility chains also merit consideration in this context, but are not the only or inevitably preferred option.

More Detailed Analysis & Review Underway

"The Role of Biomass in America's Energy Future" (RBAEF) Project

Sponsors

DOE
Energy Foundation
National Commission on Energy Policy

Participants

Dartmouth, Natural Resources Defense Council, NREL
Princeton, Michigan State University, Argonne National Lab
Union of Concerned Scientists, University of Tennessee,
Agricultural Research Service

Public Meeting

February 23, Washington